Title: Tree height and leaf drought tolerance traits shape growth responses across droughts in a temperate broadleaf forest

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Summary

- As climate change drives increased drought in many forested regions, mechanistic understanding of the factors conferring drought tolerance in trees is increasingly important. The dendrochronological record provides a window through which we can understand how tree size and traits shape growth responses to droughts.

- We analyzed tree-ring records for twelve species in a broadleaf deciduous forest in Virginia (USA) to test hypotheses on how tree height, microenvironment characteristics, and species' traits shaped drought responses across the three strongest regional droughts over a 60-year period.

- Drought tolerance (resistance, recovery, and resilience) decreased with tree height, which was strongly correlated with exposure to higher evaporative demand and solar radiation. The potentially greater rooting volume of larger trees did not confer a resistance advantage, but marginally increased recovery and resilience, in sites with low topographic wetness index. Drought tolerance was greater among species whose leaves experienced less shrinkage upon desiccation and lost turgor (wilted) at more negative water potentials.

- The tree-ring record reveals that tree height and leaf drought tolerance traits influenced growth responses during and after significant droughts in the meteorological record. As climate change-induced droughts intensify, tall trees with drought-sensitive leaves will be most vulnerable to immediate and longer-term growth reductions.

Introduction

Forests play a critical global role in climate regulation (Bonan, 2008), yet there remains enormous uncertainty as to how the forest-dominated terrestrial carbon sink will respond to climate change (Friedlingstein *et al.*, 2006). An important aspect of this uncertainty lies with physiological responses of trees to drought (Kennedy *et al.*, 2019). In many forested regions around the world, the risk of severe drought is increasing (Trenberth *et al.*, 2014; Dai *et al.*, 2018), often despite increasing precipitation (Intergovernmental Panel on Climate Change, 2015; Cook *et al.*, 2015). Droughts, intensified by climate change, have been affecting forests worldwide and are expected to continue as an important driver of forest change (Allen *et al.*, 2010, 2015; McDowell *et al.*, 2020). Understanding forest responses to drought requires elucidation of how tree size, microenvironment, and species' traits jointly influence individual-level drought tolerance, defined here as a tree's ability to maintain growth during drought (*resistance*) and recover to its pre-drought growth rate (*resilience*; Lloret *et al.*, 2011). Survival has been shown to be linked to resistance, recovery, and resilience (DeSoto *et al.*, 2020; Gessler *et al.*, 2020), implying they may be influenced by the same factors. However, it has proven difficult to resolve the many factors affecting tree growth during drought and the extent to which their influence is consistent across droughts. This is because available forest census data only rarely captures extreme drought, whereas tree-ring records capture multiple droughts but typically focus on only the largest individuals of one or a few species.

Many studies have shown that within and across species, large trees tend to be more affected by drought. Greater growth reductions (*i.e.*, lower drought resistance) in larger trees were first shown on a global scale by Bennett *et al.* (2015), and subsequent studies have reinforced this finding (*e.g.*, Pretzsch *et al.*, 2018; Gillerot *et al.*, 2020). Although lower recovery and resilience of larger trees have also been observed (Gillerot *et al.*, 2020), results are mixed (Merlin *et al.*, 2015), and a recent physiological model suggests that large trees destined to die following drought may still exhibit high recovery and resilience (Trugman *et al.*, 2018). Thus, in general we have much more limited understanding of how and why drought resilience scales with tree size.

Moreover, it has yet to be resolved which of several potential underlying mechanisms most strongly shape these trends in drought response. First, tree height itself may be a primary driver. Taller trees face the biophysical challenge of lifting water greater distances against the effects of gravity and friction (Ryan *et al.*, 2006; McDowell *et al.*, 2011; McDowell & Allen, 2015; Couvreur *et al.*, 2018). Vertical gradients in stem and leaf traits–including smaller and thicker leaves (higher leaf mass per area, LMA), greater resistance to hydraulic dysfunction (*i.e.*, more negative water potential at 50% loss of hydraulic conductivity, more negative P50), and lower hydraulic conductivity at greater heights (Koike *et al.*, 2001; McDowell *et al.*, 2011; Couvreur *et al.*, 2018)–enable trees to become tall (Couvreur *et al.*, 2018). Greater stem capacitance (*i.e.*, water storage capacity) of larger trees may also confer resistance to transient droughts (Phillips *et al.*, 2003; Scholz *et al.*, 2011). Taller trees have wider conduits in the basal portions of taller trees, both within and across species (Olson *et al.*, 2018; Liu *et al.*, 2019) and throughout the conductive systems of angiosperms (Zach *et al.*, 2010; Olson *et al.*, 2014, 2018), which help maintain constant the resistance that would otherwise increase as trees grow taller. Wider xylem conduits plausibly make large trees more vulnerable to embolism during drought (Olson *et al.*, 2018), and traits conducive to efficient water transport may also lead to poor ability to recover from or re-route water around embolisms (Roskilly *et al.*, 2019).

Larger trees may also have lower drought tolerance because of microenvironmental and ecological factors. Their crowns tend to occupy more exposed canopy positions, which are associated with higher evaporative demand (Kunert *et al.*, 2017). Counteracting the liabilities associated with tall height, large trees tend to have larger root systems (Enquist & Niklas, 2002; Hui *et al.*, 2014), potentially mitigating some of the biophysical challenges they face by allowing greater access to water. Larger root systems–if they grant access to deeper water sources–would be particularly advantageous in drier microenvironments (e.g., hilltops, as compared to valleys and streambeds) during drought. Finally, tree size-related responses to drought can be modified by species' traits and their distribution across size classes (Meakem *et al.*, 2018; Liu *et al.*, 2019). Understanding the mechanisms driving the greater relative growth reductions of larger trees during drought requires sorting out the interactive effects of height and associated exposure, root water access, and species' traits.

Debates have also arisen regarding the traits influencing tree growth responses to drought. Studies within temperate broadleaf forests have observed ring-porous species showing higher drought tolerance than diffuse-porous species (Friedrichs *et al.*, 2009; Elliott *et al.*, 2015; Kannenberg *et al.*, 2019). However, this distinction does not always hold within the biome (Martin-Benito & Pederson, 2015) or in the global context (Wheeler *et al.*, 2007; Olson *et al.*, 2020), and it does not resolve differences among the many species within each category. Commonly-measured traits including wood density and leaf mass per area (LMA) have been linked to drought responses within some temperate deciduous forests (Abrams, 1990; Guerfel *et al.*, 2009; Hoffmann *et al.*, 2011; Martin-Benito & Pederson, 2015) and across forests worldwide (Greenwood *et al.*, 2017). However, in other cases these traits could not explain drought tolerance (e.g., in a tropical rainforest; Maréchaux *et al.*, 2019), or the direction of response was not always consistent. For instance, higher wood density has been associated with greater drought resistance at a global scale (Greenwood *et al.*, 2017), but correlated negatively with tree performance during drought in a broadleaf deciduous forest in the southeastern United States (Hoffmann *et al.*, 2011). Thus, the perceived influence of these traits on drought resistance may actually reflect indirect correlations with other traits that more directly drive drought responses (Hoffmann *et al.*, 2011).

In contrast, hydraulic traits have direct physiological linkages to tree growth and mortality responses to drought. For instance, water potentials at which percent the loss of conductivity surpasses a certain threshold (e.g., P50 and P88, representing 50 and 88% loss of conductivity, respectively) and hydraulic safety margin (*i.e.*, difference between typical minimum water potentials and P50 or P88) correlate with drought performance across global forests (Anderegg *et al.*, 2016). However, these are time-consuming to measure and therefore infeasible for predicting or modeling drought responses in highly diverse forests (*e.g.*, in the tropics). More easily-measurable leaf drought tolerance traits that have direct linkage to plant hydraulic function can explain variation in plant distribution and function (Medeiros *et al.*, 2019). These include leaf area shrinkage upon desiccation (PLA_{dry}; Scoffoni *et al.*, 2014) and the leaf water potential at turgor loss point (π_{tlp}), *i.e.,* the water potential at which leaf wilting occurs (Bartlett *et al.*, 2016a; Zhu *et al.*, 2018). Both traits correlate with hydraulic vulnerability and drought tolerance as part of unified plant hydraulic systems (Scoffoni *et al.*, 2014; Bartlett *et al.*, 2016a; Farrell *et al.*, 2017; Zhu *et al.*, 2018). The abilities of both PLA_{dry} and π_{tlp} to explain the drought tolerance of tree growth remains untested (but see Powers *et al.*, 2020 for π_{tlp} link to mortality).

Here, we examine how tree height, microenvironment characteristics, and species' traits collectively shape three metrics of drought tolerance: (1) resistance, defined as the ratio of annual stem growth in a drought

125 year to that which would be expected in the absence of drought based on previous years' growth; (2)
126 recovery, defined the ratio of post-drought growth to growth during the drought year; and (3) resilience,
127 defined as the ratio of post-drought to pre-drought growth (Lloret *et al.*, 2011). We test a series of
128 hypotheses and associated specific predictions (Table 1) based on the combination of tree-ring records from
129 the three strongest droughts over a 60-year period (1950 - 2009), species trait measurements, and census
130 and microenvironmental data from a large forest dynamics plot in Virginia, USA. First, we focus on how
131 tree size, alone and in its interaction with microenvironmental gradients, influences drought tolerance. We
132 examine the contemporary relationship between tree height and microenvironment, including growing
133 season meteorological conditions and crown exposure. We then test whether, consistent with most forests
134 globally, larger-diameter, taller trees tend to have lower drought tolerance in this forest, which is in a
135 region (eastern North America) represented by only two studies in the global review of (Bennett *et al.*,
136 2015). We also test for an influence of potential access to available soil water, which should be greater for
137 larger trees in dry but not in perpetually wet microsites. Finally, we focus on the role of species' traits,
138 testing the hypothesis that species' traits--particularly leaf drought tolerance traits--predict drought
139 tolerance. We test predictions that drought tolerance is higher in ring-porous than semi-ring and
140 diffuse-porous species and that it is correlated with wood density–either positively (Greenwood *et al.*, 2017)
141 or negatively (Hoffmann *et al.*, 2011) and positively correlated with LMA. We further test predictions that
142 species with low PLA_{dry} and those whose leaves lose turgor at lower water potentials (more negative π_{tlp})
143 have higher tolerance.

Materials and Methods

144

Study site and microclimate

145

146 Research was conducted at the 25.6-ha ForestGEO (Forest Global Earth Observatory) study plot at the
147 Smithsonian Conservation Biology Institute (SCBI) in Virginia, USA (38°53'36.6"N, 78°08'43.4"W,
148 elevation 273-338 m.a.s.l.; Fig. **S1**) (Bourg *et al.*, 2013; Anderson-Teixeira *et al.*, 2015a). Climate is humid
149 temperate, with mean annual temperature of 12.7°C and precipitation of 1005 mm yr^{-1} during our study
150 period (1960-2009; source: CRU TS v.4.01; Harris *et al.*, 2014). Dominant tree taxa within this secondary
151 forest include *Liriodendron tulipifera*, oaks (*Quercus* spp.), and hickories (*Carya* spp.; Table 2).

Identifying drought years

152

153 We identified the three largest droughts within the time period 1960-2009, defining drought (Slette *et al.*,
154 2019) based on Palmer Drought Severity Index (PDSI) during May-August (MJJA; Table S1), which were
155 identified by Helcoski *et al.* (2019) as the months to which annual tree growth was most sensitive at this
156 site. PDSI divisional data for Northern Virginia were obtained from NOAA
157 (https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp) in December 2017. Based on this, the three
158 strongest droughts during the study period occurred in 1966, 1977, and 1999 (Figs. **1, S1**; Table S1).

159 The droughts differed in intensity and antecedent moisture conditions (Fig. **S1**, Table S1). The 1966
160 drought was preceded by two years of moderate drought during the growing season and severe to extreme
161 drought starting the previous fall. In August 1966, $PDSI$ reached its lowest monthly value (-4.82) of the
162 three droughts. The 1977 drought was the least intense throughout the growing season, and it was
163 preceded by 2.5 years of near-normal conditions, making it the mildest of the three droughts. The 1999
164 drought was preceded by wetter than average conditions until the previous June, but $PDSI$ plummeted

below -3.0 in October 1998 and remained below this threshold through August 1999. Following all three droughts, $PDSI$ rebounded to near-normal conditions in September or October (Fig. **S1**).

Data collection and preparation

Within or just outside the ForestGEO plot, we collected data on a suite of variables including tree heights, microenvironment characteristics, and species traits (Table 3). The SCBI ForestGEO plot was censused in 2008, 2013, and 2018 following standard ForestGEO protocols, whereby all free-standing woody stems $\geq$ 1cm diameter at breast height (DBH) were mapped, tagged, measured at DBH, and identified to species (Condit, 1998). From these census data, we used measurements of DBH from 2008 to calculate historical DBH and data for all stems $\geq$ 10cm to analyze functional trait composition relative to tree height (all analyses described below).

We analyzed tree-ring data (xylem growth increment) from 571 trees representing the twelve dominant species (Table 2; Fig. **S2**). Selected species were those with the greatest contributions to woody aboveground net primary productivity ($ANPP_{stem}$) and together comprised 97% of study plot $ANPP_{stem}$ between 2008 and 2013 (Helcoski *et al.*, 2019). Cores (one per tree) were collected within the ForestGEO plot at breast height (1.3m) in 2010-2011 or 2016-2017. In 2010-2011, cores were collected from randomly selected live trees of each species that had at least 30 individuals $\geq$ 10 cm DBH (Bourg *et al.*, 2013). In summers of 2016 and 2017, cores were collected from all trees found to have died within the preceding year based on annual tree mortality censuses (Gonzalez-Akre *et al.*, 2016). It is unlikely that drought was a factor in the death of any of these trees, as monthly May-Aug $PDSI$ did not drop below -1.75 (near-normal) in these years or the three years prior (2013-2017). Moreover, the trees analyzed here lived at least 17-18 years past the most recent major drought (1999), whereas the meta-analysis of Trugman *et al.* (2018) indicates that >10-year lags in drought-attributed mortality are rare. Having found that trees cored dead displayed similar climate sensitivity to trees cored live (Helcoski *et al.*, 2019), we pooled the samples for this analysis. Cores were sanded, measured, and crossdated using standard procedures, as detailed in (Helcoski *et al.*, 2019). The resulting chronologies (Fig. **1a**) were published in Zenodo (Gonzalez-Akre *et al.*, 2019).

For each cored tree, we combined tree-ring records and allometric equations of bark thickness to reconstruct DBH for the years 1950-2009. Prior DBH was estimated using the following equation:

$$DBH_Y = DBH_{2008} - 2 * \left[r_{bark,2008} - r_{bark,Y} + \sum_{year=Y}^{2008} r_{ring,Y} \right]$$

Here, Y denotes the year of interest, r_{ring} denotes ring width derived from cores, and r_{bark} denotes bark thickness, which was estimated from species-specific allometries based on the bark thickness data from the site (Table S2; Anderson-Teixeira *et al.*, 2015b).

Tree heights (H) were measured by several researchers for a variety of purposes between 2012 and 2019 (n=1,518 trees). Methods included direct measurements using a collapsible measurement rod on small trees (NEON, 2018) or a tape measure on recently fallen trees (this study); geometric calculations using clinometer and tape measure (Stovall *et al.*, 2018b) or digital rangefinders (Anderson-Teixeira *et al.*, 2015b; NEON, 2018); and ground-based LiDAR (Stovall *et al.*, 2018a). Rangefinders used either the tangent method (Impulse 200LR, TruPulse 360R) or the sine method (Nikon ForestryPro) for calculating heights.

202 Both methods are associated with some error (Larjavaara & Muller-Landau, 2013), but in this instance
203 there was no clear advantage of one or the other. Species-specific height allometries were developed using
204 log-log regression ($ln[H] \sim ln[DBH]$; Table S3). For species with insufficient height data to create reliable
205 species-specific allometries (n=2, JUNI and FRAM), heights were calculated from an equation developed
206 by combining the height measurements across all species. We then used these allometries to estimate H for
207 each drought year, Y, based on reconstructed DBH_Y (Fig. **S3**).

208 To characterize how environmental conditions vary with height, data were obtained from the NEON tower
209 located <1km from the study area via the neonUtilities package (Lunch *et al.*, 2020). We used wind speed,
210 relative humidity, and air temperature data, all measured over a vertical profile spanning heights from 7.2
211 m to above the top of the tree canopy (31.0 or 51.8m, depending on censor), for the years 2016-2018
212 (NEON, 2018). After filtering for missing and outlier values, we determined the daily minima and maxima,
213 which we then aggregated at the monthly scale.

214 Crown position–a categorical variable classifying trees based on exposure to sunlight–was recorded for all
215 cored trees that remained standing during the growing season of 2018 following the protocol of Jennings *et*
216 *al.* (1999). Trees were classified as follows: *dominant* trees were defined as those with crowns above the
217 general level of the canopy, *co-dominant* trees as those with crowns within the the canopy; *intermediate*
218 trees as those with crowns below the canopy level, but illuminated from above; and *suppressed* as those
219 below the canopy and receiving minimal direct illumination from above.

220 Topographic wetness index (TWI), used here as a metric of long-term mean moisture availability, was
221 calculated using the dynatopmodel package in R (Fig. **S2**) (Metcalfe *et al.*, 2018). Originally developed by
222 Beven & Kirkby (1979), TWI was part of a hydrological run-off model and has since been used for a
223 number of purposes in hydrology and ecology (Sørensen *et al.*, 2006). TWI calculation depends on an input
224 of a digital elevation model (DEM; ~3.7 m resolution from the elevatr package (Hollister, 2018)), and from
225 this yields a quantitative assessment defined by how "wet" an area is, based on areas where run-off is more
226 likely. From our observations in the plot, TWI performed better at categorizing wet areas than the
227 Euclidean distance from the stream.

228 Species' trait data were collected in August 2018 (Tables 2-3; Fig. **S4**). We sampled small, sun-exposed
229 branches up to eight meters above the ground from three individuals of each species in and around the
230 ForestGEO plot. Sampled branches were re-cut under water at least two nodes above the original cut and
231 re-hydrated overnight in covered buckets under opaque plastic bags before measurements were taken.
232 Rehydrated leaves taken towards the apical end of the branch (n=3 per individual: small, medium, and
233 large) were scanned, weighed, dried at 60° C for $\geq$ 48 hours, and then re-scanned and weighed. Leaf area
234 was calculated from scanned images using the LeafArea R package (Katabuchi, 2019). LMA was
235 calculated as the ratio of leaf dry mass to fresh area. PLA_{dry} was calculated as the percent loss of area
236 between fresh and dry leaves. Wood density was calculated for ~1cm diameter stem samples (bark and pith
237 removed) as the ratio of dry weight to fresh volume, which was estimated using Archimedes' displacement.
238 We used the rapid determination method of Bartlett *et al.* (2012) to estimate osmotic potential at turgor
239 loss point (π_{tlp}). Briefly, two 4 mm diameter leaf discs were cut from each leaf, tightly wrapped in foil,
240 submerged in liquid nitrogen, perforated 10-15 times with a dissection needle, and then measured using a
241 vapor pressure osmometer (VAPRO 5520, Wescor, Logan, UT, USA). Osmotic potential (π_{osm}) given by
242 the osmometer was used to estimate (π_{tlp}) using the equation $\pi_{tlp} = 0.832\pi_{osm}^{-0.631}$ (Bartlett *et al.*, 2012).

243 *Statistical Analysis*

For each drought year, we calculated metrics of drought resistance (Rt), recovery (Rc), and resilience (Rs), following Lloret *et al.* (2011). These metrics compare ratios of basal area increment (BAI; *i.e.*, change in cross-sectional area) before, during, and after the drought year, as specified in Table 3. For all metrics, values <1 and >1 indicate growth reductions and increases, respectively.

Because these metrics could potentially be biased by directional pre-drought growth trends, we also tried an intervention time series analysis (ARIMA, Hyndman *et al.*, 2020) that predicted mean drought-year growth based on trends over the preceding ten years and used this value in place of the five-year mean in calculations of resistance (Rt_{ARIMA}= observed BAI/ predicted BAI). Rt and Rt_{ARIMA} were strongly correlated (Fig. **S5**), and showed similar responses to the independent variables of interest (cf. Tables S4-55, S8-S9). Visual review of the individual tree-ring sequences with the largest discrepancies between these metrics revealed that Rt was less prone to unreasonable estimates than Rt_{ARIMA}. We therefore determined that use of 5-year means, as described above, were more appropriate metrics than those based on ARIMA projections.

Analyses focused on testing the predictions presented in Table 1 with Rt (or Rt_{ARIMA}), Rc, or Rs as the response variable. Models were run for all drought years combined and for each drought year individually. The general statistical model for hypothesis testing was a mixed effects model, implemented in the lme4 package in R (Bates *et al.*, 2019). In the multi-year model, we included a random effect of tree nested within species and a fixed effect of drought year to represent the combined effects of differences in drought characteristics. Individual year models included a random effect of species. All models included fixed effects of independent variables of interest (Tables 1,3) as specified below. All variables across all best models had variance inflation factors between 1 and 1.045. We used Akaike information criterion with correction for small sample sizes (AICc; see Brewer *et al.*, 2016) to assess model selection, and conditional/marginal R-squared to assess model fit as implemented in the AICcmodavg package in R (Mazerolle & Dan Linden., 2019). Individual model terms were considered significant when their addition to a model improved fit at ΔAICc $\geq$ 2.0, where ΔAICc is the difference in AICc between models with and without the trait.

To avoid over-fitting models with five species traits (Table 3) across only 12 species, we did not include all traits as fixed effects in a single linear mixed model, but rather conducted individual tests of each species trait to determine the relative importance and appropriateness for inclusion in the main model. These tests followed the model structure specified above, then added $ln[H]$ and $ln[TWI]$ to create a base model against which we tested traits. Trait variables were considered appropriate for inclusion in the main model if their addition to the base model significantly improved fit for at least one metric of drought tolerance (Rt, Rc, or Rs; Tables S4,S6-S7). While we tested xylem porosity as a predictor (Table 1), we did not consider it appropriate for inclusion in the main model because of highly uneven distribution of species across categories (Table 2) and opposite drought responses of the only two diffuse-porous species (see Results).

We then determined the top full models for predicting each dependent variable. To do so, we compared models with all possible combinations of candidate variables, including $ln[H]*ln[TWI]$ and species traits as specified above. We identified the full set of models within ΔAICc=2 of the best model (that with lowest AICc). When a variable appeared in all of these models and the sign of the coefficient was consistent across models, we viewed this as support for the acceptance/rejection of the associated prediction (Table 1). If the variable appeared in some but not all of these models, and its sign was consistent across models, we considered this partial support/rejection.

All analysis beyond basic data collection was performed using R version 3.6.2 (R Core Team, 2019). Other

R-packages used in analyses are listed in the Supplementary Information (Appendix S1).

Results

Tree height and microenvironment

In the years for which we have vertical profiles in climate data (2016-2018), taller trees–or those in dominant crown positions– were generally exposed to higher evaporative demand during the peak growing season months (May-August; Fig. **2**). Specifically, maximum daily wind speeds were significantly higher above the top of the canopy (40-50m) than within and below (10-30m) (Fig. **2a**). Relative humidity was also somewhat lower during June-August, ranging from ~50-80% above the canopy and ~60-90% in the understory (Fig. **2b**). Air temperature did not vary consistently across the vertical profile (Fig. **2c**).

Crown position varied as expected with height (dominant > co-dominant > intermediate > suppressed), but with substantial variation (Fig. **2d**). There were significant differences in height across all crown position classes (Fig. **2d**). A comparison test between height and crown position data from the most recent ForestGEO census (2018) revealed a correlation of 0.73.

Community-level drought responses

At the community level, cored trees showed substantial growth reductions in all three droughts, with a mean Rt of 0.86 in 1966 and 1999, and 0.84 in 1977 (Fig. **1b**). Across the entire study period (1950-2009), the focal drought years were the three years with the largest fraction of trees exhibiting $Rt \leq 0.7$. Specifically, in each drought, roughly 30% of the cored trees had growth reductions of $\geq 30\%$ ($Rt \leq 0.7$): 29% in 1966, 32% in 1977, and 27% in 1999. However, some individuals exhibited increased growth, *i.e.*, $Rt > 1.0$: 26% of trees in 1966, 22% in 1977, and 26% in 1999. Recovery was generally strong and complete, with Rc averaging 1.55 in 1966, 1.42 in 1977, and 1.34 in 1999 (Fig. **S6**) and Rs averaging 1.28 in 1966, 1.19 in 1977, and 1.12 in 1999 (Fig. **1c**).

In the context of the multivariate models, all response variables varied across drought years. That is, in models with all drought years combined, year was present in all of the top models – *i.e.*, models that were statistically indistinguishable (ΔAICc<2) from the best model (see footnotes on Tables S8-S11). For Rt, differences among drought years were small (<0.02; Table S8). In contrast, differences among years were larger for Rc and Rs, with coefficients for year highest in 1966, intermediate in 1977, and lowest in 1999.

Tree height, microenvironment, and drought tolerance

Taller trees (based on H in the drought year) showed stronger growth reductions during drought (*i.e.*, lower Rt) and less rebound following drought (*i.e.*, lower Rc and Rs; Table 1; Fig. **4**). Specifically, for Rt, $ln[H]$ appeared, with negative coefficient, in the best model (ΔAICc=0) and all top models when evaluating the three drought years together (Tables S8-S9). The same held true for 1966 individually, but there was no significant effect of $ln[H]$ for 1977 or 1999 individually. For Rc, $ln[H]$ appeared, with negative coefficient, in the best model without a $ln[H] * ln[TWI]$ interaction, for the three drought years together and for 1977, but not for 1966 or 1999. For Rs, again considering the best models without a $ln[H] * ln[TWI]$ interaction, there was a negative effect of $ln[H]$ for the three drought years together and for 1966 and 1977, and a non-significant negative trend in 1999.

Trees in drier microsites showed greater growth declines during drought; *i.e.*, Rt had a significantly negative response to $ln[TWI]$ across all drought years combined, and in 1977 and 1999 individually (Fig.

325 **4**, Table S8-S9). The $ln[H] * ln[TWI]$ interaction was never significant, and had a positive sign in any top
326 Rt models in which it appeared (Tables 1, S8-S9), rejecting the hypothesis that smaller trees (presumably
327 with smaller rooting volume) are more susceptible to drought in microenvironments with a deeper water
328 table. In contrast, $ln[TWI]$ did not appear in any of the best models for Rc or Rs (combined of for
329 individual years), except in interaction with $ln[H]$ (Fig. 4, Tables S10-S11). Negative $ln[H] * ln[TWI]$
330 interactions appeared in the best models for both Rc and Rs for all years combined, as well as in one
331 individual year for each (1966 for Rc, 1977 for Rs). This implies a non-significant tendency for small trees
332 to have greater recovery and resilience in wetter microhabitats, but for large trees to have greater recovery
333 and resilience in dry microhabitats.

334 *Species' traits and drought tolerance*

335 Species, as a factor in ANOVA, had significant (p<0.05) influence on all traits (wood density, LMA,
336 PLA_{dry}, and π_{tlp}), with more significant pairwise differences for wood density and PLA_{dry} than for LMA
337 and π_{tlp} (Table 2, Fig. **S4**). Drought tolerance also varied across species, overall and in each drought year
338 (Figs. **3, S7**). Species with overall lowest and highest Rt and Rs were, respectively, *Liriodendron tulipifera*
339 (mean $Rt = 0.66$, mean $Rs = 1.04$) and *Fagus grandifolia* (mean $Rt = 0.99$; mean $Rs = 1.65$). These two
340 species–notably the only two diffuse-porous species in our study–differed significantly from one another in
341 Rt and Rs in each drought year (Fig. **3**).

342 Wood density, LMA, and xylem porosity were all poor predictors of drought tolerance (Tables 1, S4-S5).
343 Wood density and LMA were never significantly associated with Rt, Rc, or Rs in the single-variable tests
344 and were therefore excluded from the full models. Xylem porosity had no significant influence on Rt or Rs
345 in models for all droughts combined (Tables S4, S7). In contrast, Rc was significantly higher in diffuse- and
346 semi-ring porous species than in ring-porous species (Table S6, Fig. 3).

347 Drought resistance and resilience, but not recovery, were negatively correlated with PLA_{dry} and π_{tlp} (Fig.
348 **4**; Tables 1, S4-S11). For Rt, PLA_{dry} had a significant influence, with negative coefficient, in top models
349 for the three droughts combined and for the 1966 drought individually (Fig. **4**; Tables S8-S9). It was also
350 included in some of the top models for 1999 (Tables S8-S9). π_{tlp} was included with a negative coefficient in
351 the best model for the combined droughts scenario and for the 1977 drought individually (Fig. **4**; Table
352 S8), although its influence was not significant at ΔAICc<2. It was also included in some of the top models
353 for 1999 (Tables S8-S9).

354 Recovery was not significantly correlated with either PLA_{dry} or π_{tlp}. There was only one best Rc model
355 containing one of these terms (π_{tlp} in 1977 drought), but in no instance was one of these terms included in
356 all top models (i.e., at ΔAICc<2).

357 For Rs, PLA_{dry} was in the best models for the three droughts combined and for the 1966 drought
358 individually, and some of the top models for 1977 and 1999 (Fig. **4**; Table S11); however, its effects were
359 not significant at ΔAICc<2. π_{tlp} was in the best models for the three droughts combined and for 1966 and
360 1999 individually, and in one of the top models for 1977 (Fig. **4**; Table S11). However, its effects were
361 significant at ΔAICc<2 for 1999 only.

10

Discussion

Tree height, microenvironment, and leaf drought tolerance traits shaped tree growth responses across three droughts at our study site (Table 1, Fig. **4**). Taller trees had greater exposure to conditions that would promote water loss and heat damage during drought (Fig. **2**), which is one plausible mechanism for their lower drought resistance, recovery, and resilience (Fig. **4**). There was no evidence that greater availability of, or access to, soil water availability increased drought resistance; in contrast, trees in wetter topographic positions had lower Rt (Zuleta *et al.*, 2017; Stovall *et al.*, 2019), and the larger potential rooting volume of large trees provided no advantage in the drier microenvironments. The negative effect of height on Rt held after accounting for species' traits, which is consistent with recent work finding height had a stronger influence on mortality risk than forest type during drought (Stovall *et al.*, 2020). Drought tolerance was not consistently linked to species' LMA, wood density, or xylem type (ring- vs. diffuse porous), but was negatively correlated with leaf drought tolerance traits (PLA_{dry}, π_{tlp}). This is the first study to our knowledge linking PLA_{dry} and π_{tlp} to growth reduction during drought. The directions of these responses were consistent across droughts (Table S8), supporting the premise that they were driven by fundamental physiological mechanisms. However, the strengths of each predictor varied across droughts (Fig. **4**; Tables S8-S9), indicating that drought characteristics interact with tree size, microenvironment, and traits to shape which individuals are most affected. These findings advance our knowledge of the factors that make trees vulnerable to stem growth declines during drought and, by extension, likely make them more vulnerable to mortality (Sapes *et al.*, 2019).

The droughts considered here were of a magnitude that has occurred with an average frequency of approximately once every 10-15 years (Fig. **1a**, Helcoski *et al.*, 2019) and had substantial but short-lived impacts on tree growth (Fig. **1**). These droughts were classified as severe ($PDSI < $ -3.0; 1977) or extreme ($PDSI < $ -4.0; 1966, 1999) at our site and have been linked to tree mortality in the eastern United States (Druckenbrod *et al.*, 2019), but were modest compared to the so-called "megadroughts" that have triggered massive tree die-off in other regions (e.g., Allen *et al.*, 2010; Clark *et al.*, 2016; Stovall *et al.*, 2019). Of the droughts considered here, the 1966 drought, which was preceded by two years of dry conditions (Fig. **S1**), severely stressed a larger portion of trees (Fig. **1b**). The tendency for large trees to have lowest resistance was most pronounced in this drought, consistent with other findings that this physiological response increases with drought severity (Bennett *et al.*, 2015; Stovall *et al.*, 2019). Across all three droughts, the majority of trees experienced reduced growth, but a substantial portion (e.g., short understory trees, species with drought resistant traits) had increased growth (Figs. **1b, 4**), consistent with prior observations that smaller trees can exhibit increased growth rates during drought (Bennett *et al.*, 2015). Growth rebounded strongly following the droughts, on average exceeding pre-drought growth rates (Fig. 1), particularly for shorter trees and species with drought-tolerant traits (Figs. **3-4**). It is likely because of the moderate impact of these droughts, along with other factors influencing tree growth (e.g., stand dynamics), that our best models characterize only a modest amount of variation in Rt, Rc, and Rs: 11-18% for all droughts combined, and 13-30% for individual droughts (Tables S8-S11).

Consistent with studies in other forests worldwide (Bennett *et al.*, 2015), taller trees in this forest exhibited lower drought resistance–and also recovery and resilience–when compared to smaller trees. Mechanistically, this is consistent with, and reinforces, previous findings that it is impossible for trees to efficiently transport water to great heights and simultaneously maintain strong resistance and resilience to drought-induced embolism (Couvreur *et al.*, 2018; Olson *et al.*, 2018; Roskilly *et al.*, 2019). Taller trees also

face dramatically different microenvironments (Fig. **2**). They are exposed to higher wind speeds and lower humidity (Fig. **2a-b**), resulting in higher evaporative demand. Unlike other temperate forests where modestly cooler understory conditions have been documented (Zellweger *et al.*, 2019), particularly under drier conditions (Davis *et al.*, 2019), we observed no significant variation in air temperatures across the vertical profile (Fig. **2c**). More critically for tree physiology, leaf temperatures can become significantly elevated over air temperature under conditions of high solar radiation and low stomatal conductance (Campbell & Norman, 1998; Rey-Sánchez *et al.*, 2016). Under drought, when direct solar radiation tends to be higher (because of less cloud cover) and less water is available for evaporative cooling of the leaves, trees with sun-exposed crowns may not be able to simultaneously maintain leaf temperatures below damaging extremes and avoid drought-induced embolism. Indeed, previous studies have shown lower drought resistance in more exposed trees (Liu & Muller, 1993; Suarez *et al.*, 2004; Scharnweber *et al.*, 2019). Unfortunately, collinearity between height and crown exposure in this study (Fig. **2d**) makes it impossible to confidently partition causality. Additional research comparing drought responses of early successional and mature forest stands, along with short and tall isolated trees, would be valuable for more clearly disentangling the roles of tree height and crown exposure.

Belowground, taller trees would tend to have larger root systems (Enquist & Niklas, 2002; Hui *et al.*, 2014), but this does not necessarily imply that they have greater access to or reliance on deep soil-water resources that may be critical during drought. While tree size can correlate with the depth of water extraction (Brum *et al.*, 2019), the linkage is not consistent. Shorter trees can vary broadly in the depth of water uptake (Stahl *et al.*, 2013), and larger trees may allocate more to abundant shallow roots that are beneficial for taking up water from rainstorms (Meinzer *et al.*, 1999). Moreover, reliance on deep soil-water resources can actually prove a liability during severe and prolonged drought, as these can experience more intense water scarcity relative to non-drought conditions (Chitra-Tarak *et al.*, 2018). In any case, the potentially greater access to water did not override the disadvantage conferred by height–and, in fact, greater moisture access in non-drought years (here, higher TWI) appears to make trees more sensitive to drought (Zuleta *et al.*, 2017; Stovall *et al.*, 2019). This may be because moister habitats would tend to support species and individuals with more mesophytic traits (Mencuccini, 2003; Bartlett *et al.*, 2016b; Medeiros *et al.*, 2019), potentially growing to greater heights (e.g., Detto *et al.*, 2013), and these are then more vulnerable when drought hits. The observed height-sensitivity of *Rt*, together with the lack of conferred advantage to large stature in drier topographic positions, agrees with the concept that physiological limitations to transpiration under drought shift from soil water availability to the plant-atmosphere interface as forests age (Bretfeld *et al.*, 2018), such that tall, dominant trees are the most sensitive in mature forests. Again, additional research comparing drought responses across forests with different tree heights and water availability would be valuable for disentangling the relative importance of above- and belowground mechanisms across trees of different size.

The development of tree-ring chronologies for the twelve most dominant tree species at our site (Bourg *et al.*, 2013; Helcoski *et al.*, 2019) gave us the sample size to compare historical drought responses across species (Fig. **3**) and associated traits at a single site (see also Elliott *et al.*, 2015). Our study reinforced current understanding (see Introduction) that wood density and *LMA* are not reliably linked to drought tolerance (Table 1). Contrary to several previous studies in temperate deciduous forests (Friedrichs *et al.*, 2009; Elliott *et al.*, 2015; Kannenberg *et al.*, 2019), we did not find an association between xylem porosity and drought resistance or resilience, as the two diffuse-porous species, *Liriodendron tulipifera* and *Fagus grandifolia*, were at opposite ends of the *Rt* spectrum (Fig. **3**). While the low *Rt* of *L. tulipifera* is

consistent with other studies (Elliott *et al.*, 2015), the high Rt of *F. grandifolia* contrasts with studies identifying diffuse porous species in general (Elliott *et al.*, 2015; Kannenberg *et al.*, 2019), and the genus *Fagus* in particular (Friedrichs *et al.*, 2009), as drought sensitive. There are two potential explanations for this discrepancy. First, other traits can and do override the influence of xylem porosity on drought resistance. Ring-porous species are restricted mainly to temperate deciduous forests, while highly drought-tolerant diffuse-porous species exist in other biomes (Wheeler *et al.*, 2007). *Fagus grandifolia* had intermediate π_{tlp} and low PLA_{dry} (Fig. **S4**), which would have contributed to its drought tolerance (Fig. **4**; see discussion below), in concordance with studies identifying *Fagus* species as intermediate in drought tolerance (Pretzsch *et al.*, 2018; Vitasse *et al.*, 2019). A second explanation of why *F. grandifolia* trees at this particular site had higher Rt and Rs is that the sampled individuals, reflective of the population within the plot, are generally shorter and in less-dominant canopy positions compared to most other species (Fig. **S4**). The species, which is highly shade-tolerant, also has deep crowns (Anderson-Teixeira *et al.*, 2015b), implying that a lower proportion of leaves would be affected by harsher microclimatic conditions at the top of the canopy under drought (Fig. **2**). Thus, the high Rt and Rs of the sampled *F. grandifolia* population can be explained by a combination of fairly drought-resistant leaf traits, shorter stature, and a buffered microenvironment.

Concerted measurement of tree-rings and leaf drought tolerance traits of emerging importance (Scoffoni *et al.*, 2014; Bartlett *et al.*, 2016a; Medeiros *et al.*, 2019) allowed novel insights into the role of drought tolerance traits in shaping drought response. The finding that PLA_{dry} and π_{tlp} can be useful for predicting drought responses of tree growth (Fig. **4**; Table 1) is both novel and consistent with previous studies linking these traits to habitat and drought tolerance. Previous studies have demonstrated that π_{tlp} and PLA_{dry} are physiologically meaningful traits linked to species distribution along moisture gradients (Maréchaux *et al.*, 2015; Fletcher *et al.*, 2018; Zhu *et al.*, 2018; Medeiros *et al.*, 2019; Rosas *et al.*, 2019; Simeone *et al.*, 2019), and our findings indicate that these traits also influence drought responses. Furthermore, the observed linkage of π_{tlp} to Rt in this forest aligns with observations in the Amazon that π_{tlp} is higher in drought-intolerant than drought-tolerant plant functional type. Further, it adds support to the idea that this trait is useful for categorizing and representing species' drought responses in models (Powell *et al.*, 2017). Because both PLA_{dry} and π_{tlp} can be measured relatively easily (Bartlett *et al.*, 2012; Scoffoni *et al.*, 2014), they hold promise for predicting drought growth responses across diverse forests. The importance of predicting drought responses from species traits increases with tree species diversity; whereas it is feasible to study drought responses for all dominant species in most boreal and temperate forests (e.g., this study), this becomes difficult to impossible for diverse tropical forests where most species do not form annual rings (but see Schöngart *et al.*, 2017 for a review of progress in tropical dendroecology). A full linkage of drought tolerance traits to drought responses would be invaluable for forecasting how little-known species and whole forests will respond to future droughts (Christoffersen *et al.*, 2016; Powell *et al.*, 2017).

As climate change drives increasing drought in many of the world's forests (Trenberth *et al.*, 2014; Intergovernmental Panel on Climate Change, 2015), the fate of forests and their climate feedbacks will be shaped by the biophysical and physiological drivers observed here. Our results show that taller, more exposed trees and species with less drought-tolerant leaf traits will be most affected in terms of both growth during the drought year and subsequent growth. Survival is linked to resistance and resilience (DeSoto *et al.*, 2020; Gessler *et al.*, 2020), implying it may be influenced by the same factors. Indeed, while no link between PLA_{dry} or π_{tlp} on drought survival has been established (but see Powers *et al.*, 2020),

taller trees have lower survival (Bennett *et al.*, 2015; Stovall *et al.*, 2019). As climate change-driven droughts affect forests worldwide, there is likely to be a shift from mature forests with tall, buffering trees to forests with a shorter overall stature (McDowell *et al.*, 2020). At this point, species whose drought tolerance relies in part on existence within a buffered microenvironment (e.g., *F. grandifolia*) could in turn become more susceptible. Here, the relative importance of tree height *per se* versus crown exposure becomes crucial, shaping whether the dominant trees of shorter canopies are significantly more drought tolerant because of their shorter stature, or whether high exposure makes them as vulnerable as the taller trees of the former canopy. Studies disentangling the influence of height and exposure on drought tolerance will be critical to answering this question. Ultimately, distributions of tree heights and drought tolerance traits across broad moisture gradients suggest that forests exposed to more drought will shift towards shorter stature and be dominated by species with more drought-tolerant traits (Bartlett *et al.*, 2016a; Zhu *et al.*, 2018; Liu *et al.*, 2019). Our study helps to elucidate the mechanisms behind these patterns, opening the door for more accurate forecasting of forest responses to future drought.

Author Contribution

KAT, IM, and AJT designed the research. Tree-ring chronologies were developed by RH under guidance of AJT and NP. Trait data were collected by IM, JZ under guidance of NK and LS. Other plot data were collected by IM, AS, EGA, and NB under guidance of EGA and WM. Data analyses were performed by IM under guidance of KAT and VH. KAT and IM interpreted the results. IM and KAT wrote the first draft of manuscript, and all authors contributed to revisions.

Data and code availability

All data, code, and results are available through the SCBI-ForestGEO organization on GitHub (https://github.com/SCBI-ForestGEO: SCBI-ForestGEO-Data and McGregor_climate-sensitivity-variation repositories), with static versions corresponding to data and analyses presented here archived in Zenodo (DOIs: 10.5281/zenodo.3604993 and *[TBD]*, respectively. Full ForestGEO census data for SCBI are available through the ForestGEO data portal (www.forestgeo.si.edu).

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Supplementary Information

NEED TO UPDATE !!** Table S1. Monthly Palmer Drought Severity Index (PDSI), and its rank among all years between 1950 and 2009 (driest=1), for focal droughts.

Table S2. Species-specific bark thickness regression equations.

Table S3. Species-specific height regression equations.

Table S4. Individual tests of species traits as drivers of drought resistance, where Rt is used as the response variable.

Table S5. Individual tests of species traits as drivers of drought resistance, where Rt_{ARIMA} is used as the response variable.

Table S6. Summary of top full models for each drought instance, where Rt is used as the response variable.

Table S7. Summary of top models for each drought instance, where Rt_{ARIMA} is used as the response variable.

Figure S1. Time series of Palmer Drought Severity Index (PDSI) for the 2.5 years prior to each focal drought

Figure S2. Map of ForestGEO plot showing topographic wetness index and location of cored trees

Figure S3. Distribution of reconstructed tree heights across drought years.

Figure S4. Distribution of independent variables by species.

Figure S5. Comparison of Rt and Rt_{ARIMA} results, with residuals, for each drought scenario

Figure S6. Visualization of best model, with data, for all droughts combined.

Appendix S1. Further Package Citations

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